Elimination of DC Current Injection from a Single-Phase Grid Inverter

Ashraf Ahmed   Li Ran   Jim R. Bumby

Abstract-- **Single-phase voltage source inverters are used for connecting small scale renewable energy sources to the low voltage distribution network. They operate to supply the network with sinusoidal current. If output transformers are not used, these inverters must prevent excessive DC current injection, which may cause detrimental effects in the network. In this study, the causes of DC current injection in a common inverter topology used are analyzed. A measurement circuit of the DC current component is proposed which is then used to control the inverter for the objective of DC current injection elimination. Characteristics of the proposed method are illustrated using simulation and experimental results.**

Index Terms—**DC current injection, H-bridge inverter, signal –noise ration, closed-loop control, measurement, filter.**

I. Introduction

Single-phase voltage source inverters are increasingly used in small scale domestic renewable energy systems. The inverter as an essential stage in the system is required to produce sinusoidal AC current into the low voltage distribution network with high quality. The quality requirements cover such aspects as the total harmonic distortion (THD) level, DC current injection and power factor. The work described in this paper is concerned with the risk of DC current injection into the network from these small scale single-phase inverters without output transformers. Due to approximately short circuit characteristic of an AC network under a DC voltage excitation, a little DC voltage component that can be accidently produced by the inverter will produce large DC current injection. This causes detrimental effects on the network components in particular the network transformers which can saturate, resulting in irritant tripping. This may also increase the losses in and reduce the lifetime of the transformers, if not tripped. Moreover, the existence of the DC current component can induce metering errors and malfunction of protection relays. There are thus stringent regulations in many countries to prevent the network from large DC current injection [1], and this paper presents a new method of complying with such a requirement by an inverter that does not have a network side output transformer [2].

Using a low frequency output transformer to block the DC current component increases the cost and the size of the inverter while reduces the overall system efficiency [3-4]. An alternative solution to the DC current injection problem is to use feedback control loop to eliminate the DC offset in the inverter output voltage and such an approach is adopted in this study. Although this was also adopted in previous studies [3-5], a challenge remains to be further addressed is the accurate measurement of the usually very small DC current component mixed in a large AC current. Reference [3] proposes a method of auto-calibrating the current sensing device to remove its error. The DC current component on the AC output side of the inverter is deduced from the reading of the calibrated current sensor on the DC side, assuming the knowledge of the inverter switching pattern. This method can reduce the DC current injection but will not eliminate it because it only intends to compensate the DC current injection due to inaccuracy in the PWM process while DC current component caused by unequal on-state voltage of the semiconductor devices in the inverter cannot be compensated. Furthermore the method is subject to the influence of noises and achieves its objective at the cost of increased inductance between the DC link capacitor bank and the inverter bridge, which should ideally be kept as low as possible to constrain switching transient and avoid EMC problems.

Following the approach of active control as described in reference [3], this study proposes a new method of measuring the DC component in the output current of the inverter. The output current is measured by a resistive shunt and the obtained voltage signal processed by a specially designed and tuned analogue filter to increase the signal-noise ratio so that the DC current level as specified in standards, e.g. 20 mA, becomes measurable. The response is adequately fast even for renewable energy systems which are normally working under variable conditions. This paper explains the design of the filter circuit and the use of it in a closed loop control system aiming to keep the DC current injection low – below the standard limit. System performance is illustrated by simulation and experimental results. The study focuses on a full bridge voltage source inverter operating in a unipolar PWM mode. The block diagram of the transformer-less inverter under study is depicted in Fig. 1 showing only the control for DC current injection compensation.

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II. Causes of DC Current Injection

There are three main factors which can cause DC current injection into the network from a single-phase H-bridge voltage source inverter. These are:

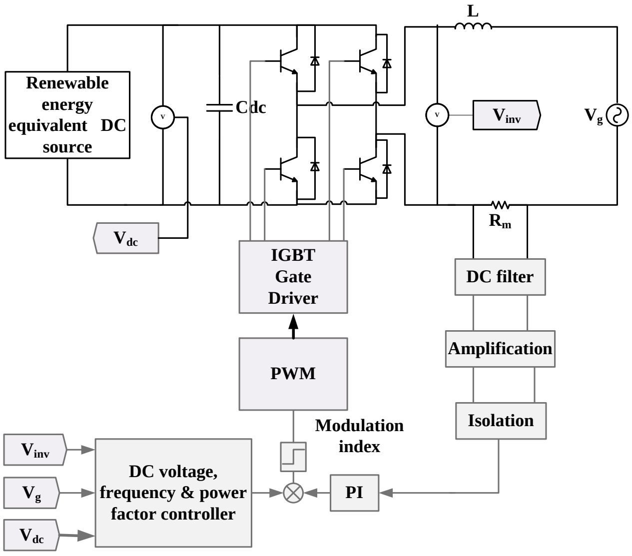

Fig. 1 Simple grid connected inverter circuit

- Unequal semiconductor device characteristics in the inverter including on-state resistance and on-state forward saturation voltage, and the temperature coefficients of these parameters. The device characteristics are affected by inevitable variations during fabrication and packaging and can also drift in operation due to degradation mechanisms such as bond wire lift-off. Simulation was performed assuming that the on-state voltage of the IGBT devices in the inverter is unbalanced by 0.05 V. For a typical 230 V single-phase feeder in the UK, the series resistance in the Thevenin equivalent circuit representation would be 0.01-0.04 Ω. For a typical modulation depth of 0.8 in the inverter and 1 kW output power at unity power factor, simulation showed that the DC current injection is between 375 mA and 1500 mA. This shows how difficult it is to comply with typical standard requirement of DC current injection being less than e.g. 20 mA. The only way is probably to set the DC current under close-loop control if a low frequency output transformer is to be avoided, which however depends on how accurately the weak signal of a small DC current can be obtained.
- DC bias that can be included in the inverter PWM switching process. This is particularly vulnerable to the blanking time between the upper and lower switches in the same leg of the bridge. Simulation shows that DC current injection in the range of hundreds of mA can be easily reached with unbalance of blanking time in a few microseconds between the positive and negative half cycles of the inverter output.
- DC bias of output current sensor.

III. DC Current Elimination Topologies

The inclusion of a low frequency (50 or 60 Hz) isolation transformer at the output of the inverter eliminates the injection of DC current on the grid side. Drawbacks of using this type of transformer are the added cost, weight, and size to the inverter system, and the reduced overall efficiency. A low frequency transformer is more bulky than a high frequency isolation transformer which however cannot prevent DC current injection into the grid. Furthermore, using half bridge inverter will eliminate the DC current injection due to that there is always one of the two DC link capacitors in the path of the current. The drawbacks of using half bridge inverter are the higher ratings of the DC capacitors and IGBTs, and the need of doubling the value of the input DC link voltage as compared to the H-bridge inverter; this increases the cost and losses of the inverter.

In the approach that is further pursued in this study, the DC component in the output current is sensed and used in the controller to eliminate the DC current injection. One of the challenges to this approach is the accuracy, and that is due to the relatively small amount of DC current component that needs to be accurately measured. As an illustration of this problem, for a 5 kW inverter the 20 mA DC components, which is the required specification in the UK and Australia, is less than 0.1% of the fundamental component, and this is not easily measurable due to the offset and accuracy in the current measurement device. Another problem is the resolution where a very high DSP resolution is needed to measure the current directly from the line and analyse it to find the DC component by filtering or FFT analysis, which increases the system cost.

IV. Proposed DC Current Injection Measurement and Controller Design

A circuit based on a resonance approach is used for measuring the DC component in the current. The circuit is shown in Fig. 2, where resistor R_a is the resistive current shunt in the path of the inverter output current. The series LC resonance circuit is used to bypass the majority of the fundamental AC component of the measured voltage across the shunt and block the DC component so that the entire DC component of the shunt resistor voltage will be applied across the resistor $R_{m,}$ across which V_m is measured, as an indication of the DC component contained in the inverter output current. V_m also contains a residual of the 50 Hz (or 60 Hz) AC

component that has not been filtered out. But for the reason to become clear later, this has little effect as long as the majority of the AC component has been bypassed and the signal-noise ratio regarding the targeted DC component in the measured current shunt voltage is significantly improved.

The value of the inductance L_b is chosen according to the filter rating where L_b blocks the mains AC current component and it is a short circuit to the DC component. L_b can be chosen according to

$$L_b = \frac{R_a}{\omega} \frac{I_{main}}{I_b} \tag{1}$$

where (ω) is the mains frequency (rad/s), I_b the AC current through L_b, and I_{main} the inverter output mains current. The value of inductance L_m is chosen to give some tolerance in L_{res} and C_{res} in the series resonant branch. To choose the precise value for the resistance R_m, consider the steady state transfer functions from the DC or fundamental AC component in the inverter output current to the corresponding components in V_m. Fig. 3 shows that as R_m increases both the DC and AC components (gains) of the filter increase, but the increase of the DC gain saturates as R_m approaches 10 Ω. Taking into account the maximum input value for the amplifier and the tolerance in the passive filter components (L_{res} and C_{res}), a value between 4Ω and 7Ω can be chosen for R_m.

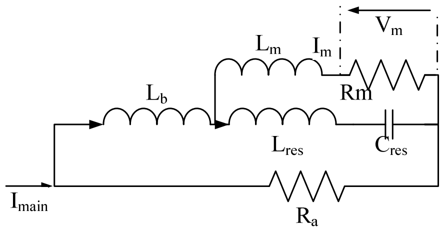

Fig. 2 DC current injection measurement circuit

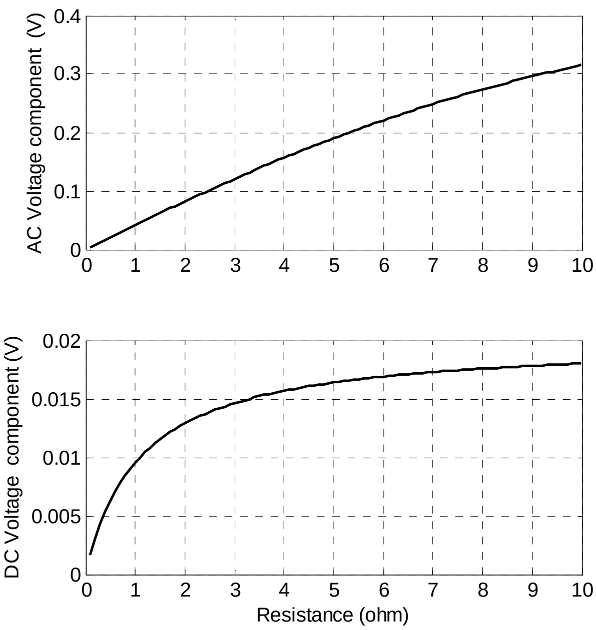

Fig. 3 Choosing filter output resistance R_m

The transfer function from the mains current to the filter output voltage can be derived as below.

$$G_m = \frac{R_m R_a (sL_r + \frac{1}{sC_r})}{((R_a + sL_b)(R_m + s(L_m + L_r) + \frac{1}{sC_r})(R_a + sL_b) + (sL_r + \frac{1}{sC_r})(R_m + sL_m))} \tag{2}$$

To simplify the system model, the causes of DC current injection are collectively represented as a DC voltage source at the inverter output (V_s) as shown in Fig. 4, while the compensating voltage produced by off-setting the modulation index of the inverter is considered a controllable DC voltage source (V_c). The inverter control will also respond to the residual fundamental AC component in V_m. The response is small compared to the normal inverter output voltage. The grid exhibits series inductance (L_f) and resistance (R_f). The transfer function from the inverter output voltage to the current is

$$G_s = \frac{K_s}{1 + sT_s} \tag{3}$$

where $K_s = 1/R_f$ and $T_s = L_f / R_f$.

The block diagram of the closed-loop control system is shown in Fig. 5 where a PI controller is used to control the DC component of the current by off-setting the modulation index of the inverter. In the design of the controller, disturbance rejection and noise suppression were taken into account [6]. The Matlab control toolbox is used to design the controller.

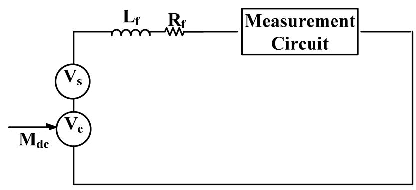

Fig. 4 Circuit simplification for analysis of the DC current

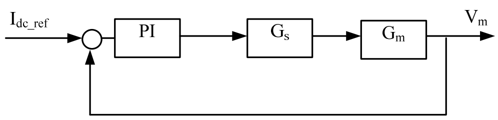

Fig. 5 Control block diagram

V. Simulation Results

The time-domain simulation was carried out using Matlab/ Simulink for a simplified system configuration as shown in Fig. 1. The DC link is a controlled voltage source emulating the renewable energy source supplying a single-phase grid connected H-bridge inverter. The DC link voltage is maintained to be constant at 400 V and the inverter is controlled to supply the grid with 2.5 kW power with unity power factor. Unequal on-state state voltages between the inverter arms are adjusted to produce a DC current of 20 mA injected into the grid while the DC current elimination controller is applied at t=1 s from the start of the simulation.

The simulation results are shown in Fig. 3 , which illustrates the mains current (I_{main}), the mains DC current component ($I_{main-DC}$), the filter output (V_m), and the DC component in the filter output voltage (V_{m-DC}). The simulation results demonstrate that the DC current can be eliminated by the controller and this proves the controller design based on a simplified method. Furthermore, the filter increases the signal-noise ratio of the DC component in V_m with respect to the residual AC component which is regarded as noise. The DC component in V_m becomes measurable after amplification. To demonstrate that, the DC current component in the mains current is less than 0.2% while it is more than 5% in the output of the filter, corresponding to a 25 times improvement of the signal-noise ratio.

VI. Experimental Verification

Block diagram of the experimental test rig setup is shown in Fig. 4 where a DC voltage source is connected to the H-bridge inverter, which supplies a passive load. To artificially cause a DC component in the inverter output current, a circuit of variable resistance connected to a diode is paralleled to the load resistance as shown in Fig. 7. The controller for DC current injection elimination and the inner loop for the inverter PWM process are programmed in Matlab/Simulink and implemented using an embedded dSPACE real time control system [7]. The filter output is measured as shown in Fig. 4 and provided to the controller where the H-bridge inverter PWM control signals are generated. The DC current injection elimination control is applied after 18 seconds from the start of the experiment.

The experimental results are shown in Fig. 5 and Fig. 6 where the data were collected on a digital scope and dSPACE respectively. Fig. 8 shows the inverter output current before DC component elimination, which contains a DC component. Fig. 6 shows the output voltage of the measuring filter circuit, V_m. The variable resistance was adjusted to produce almost 12.3 mA DC component in the inverter output current whose fundamental AC component is approximately 1.06 A, as shown in Fig. 8.

It is clearly shown in Fig. 6 that the controller eliminates the DC current component to an insignificant level. Furthermore, the test results show that as the inverter output current changes the controller keeps the DC-injected current at the same level, which remains to be insignificant. This is particularly useful in renewable energy systems where the input power is always fluctuating.

The experimental results show a slight divergence from the expected ideal characteristics and this is due to the tolerance of the passive filter component values. With this, the filter can still adequately sense the DC component in the inverter output current. As a demonstration, the DC component is only 0.8% in the inverter output current while it is almost 13% in the filter output voltage signal. Consequently, the objective of the research has been achieved.

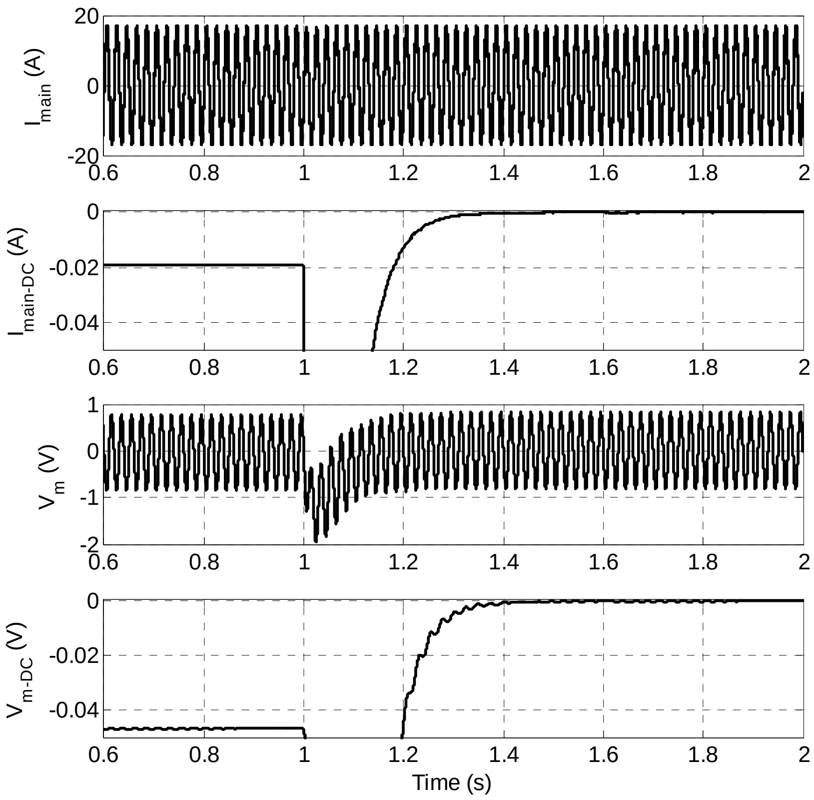

Fig. 3 Time-domain simulation results

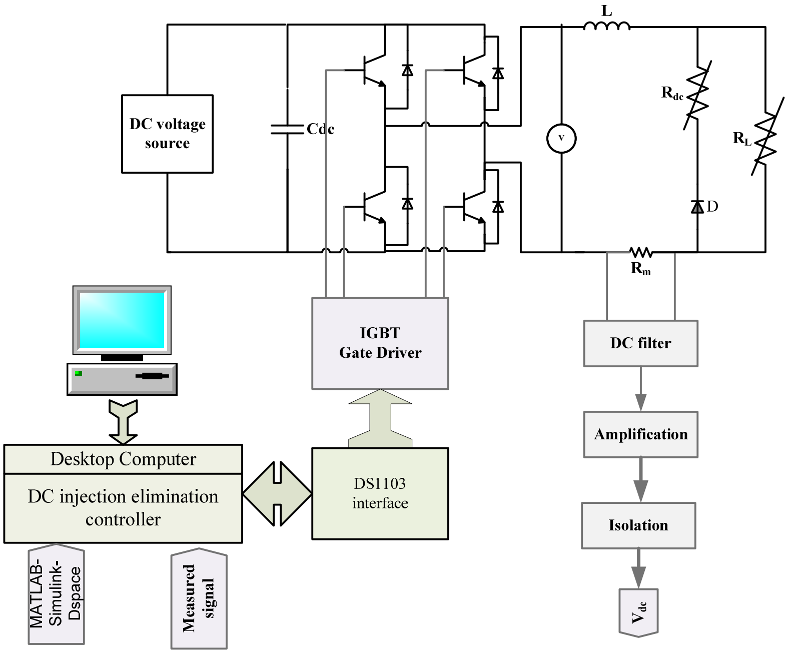

Fig. 4 The experimental test rig Configuration

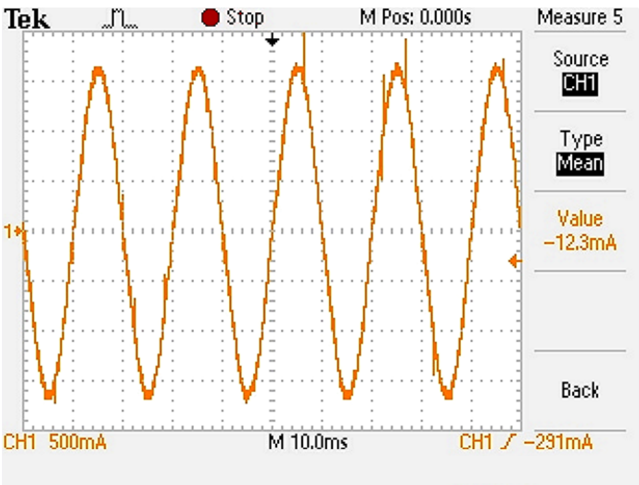

Fig. 5 Measured inverter output current

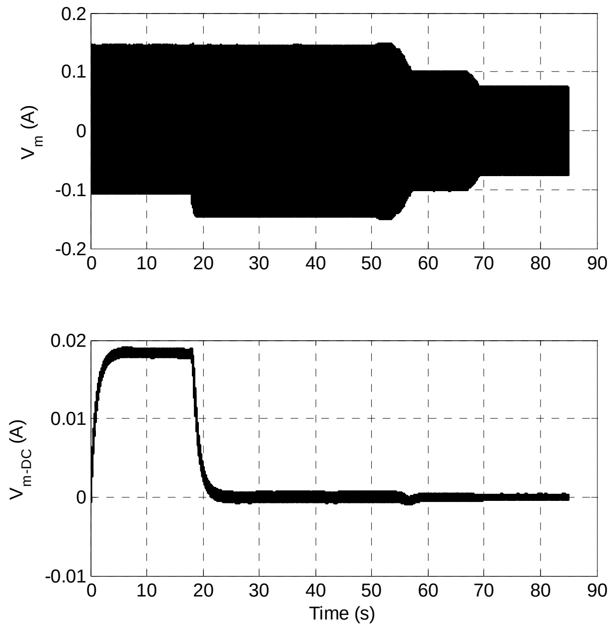

Fig. 6 Experimental results

VII. Conclusion

DC current injection is of growing concern due to the increasing usage of single-phase inverters as the demand for small scale renewable power generation increases. One of the challenges to eliminate the DC current injection is to accurately measure the small DC component contained in the inverter output current. This is particularly difficult as the fundamental AC current component is relatively large.

In this paper, a method to eliminate the DC current injection of a single-phase H-bridge inverter is proposed. The proposed method is based on designing a passive filter to make the DC component more measurable in the filter output. A simplified method to design the compensating control was proposed for the inverter PWM process.

The method has been verified by both simulation and experimental test. The simulation and experimental results demonstrate that the proposed method improves the accuracy of measuring of the very small DC current component. This improvement helps removing the DC component to meet the obligatory local and international standards.

VIII. REFERENCES

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